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THE APPLICATION OF DATA ON STRENGTH UNDER REPEATED STRESSES TO THE DESIGN OF AIRCRAFT

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THE APPLICATION OF DATA ON STRENGTH UNDER REPEATED STRESSES TO THE DESIGN OF AIRCRAFT

By L. R. Jackson and H. J. Grover

SUMMARY

This report suggests a method whereby information on the strength under repeated stresses of aircraft materials or structural parts can be used in conjunction with information on service loadings as a means of comparing alternative designs. The method has been developed around information on repeated loading in service caused by gusts, because there are, at present, more data available on loads from this source.

The method of analysis is flexible enough that information on repeated loadings from other sources than gusts can be added whenever such data become available.

Using the method developed, a number of specific examples have been worked out illustrating the comparative life of various types of aircraft joints. The examples also provide information as to the range in gust velocity responsible for the most damage to the joints.

INTRODUCTION

The tendency toward higher wing loading and lower load factors for large aircraft has made it important to find out whether this design trend might result in some failures from fatigue.

This report combines available flight data with information on the fatigue strength of aircraft structural elements to illustrate what can be done with present information to predict the life of aircraft elements under the types of repeated stresses which result from gusts.

The report is divided into four sections.

The first section discusses relations between gust velocity, load factors, and stresses in aircraft elements.

The second section discusses those sections of Rhode and Donely's recent report (reference 1) on the "Frequency of Occurrence of Atmospheric Gusts and of Related Loads on Airplane Structures" that pertain to this analysis.

The third section discusses available information on the fatigue strength of some aircraft structural elements made from 24S-T Alclad and 17S-T.

The fourth section presents a method of combining the gust data with the information on fatigue strength to predict the life of structural elements in aircraft.

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I. RELATIONS BETWEEN GUST VELOCITY, LOAD FACTORS, AND STRESSES IN AIRCRAFT ELEMENTS

In order to apply fatigue data to the effect of gusts on airplanes, it is necessary to define the conditions under which the application is made.

A loaded airplane when in straight, level flight in still air is defined as operating under a load factor of 1 in g units.

For some time, the design criterion for airplanes has been that they shall be able to withstand the acceleration produced by a 30-foot-per-second gust without a permanent set being produced and a load 1.5 times as great without failure.

The first step in applying these criteria to fatigue data is to determine the increment in load factor produced by a gust of any given magnitude.

Considering the airplane as a rigid body, the relation between gust velocity and increment in acceleration can be expressed by the equation:

$$\Delta n = K_1 U_e \qquad (1)$$

where Δn is the increment in load factor (or acceleration in g units) and U_e is the effective gust velocity in feet per second. The factor K_1 is a function of the design of the airplane and the airspeed at which the airplane encounter the gust U_e.

For conditions of straight, level flight the factor K_1 is given by the equation:

$$K_1 = \frac{\rho_0}{2} \frac{akVe}{\frac{W}{S}} \qquad (2)$$

(See reference 1, p. 4.)

In this equation ρ_0 is the mass density of air at sea level = 0.002378 slugs per cubic foot. The term K is terme by Rhode and Donely (reference 1, p. 4) the "relative alleviation factor" and allows for the relative mass effect on the response of the airplane to a gust. Figure 1 (reference 1) shows the variation in this factor with wing loading. The term Ve is the equivalent air speed, indicated airspeed corrected for installation and instrument errors in feet per second; $\frac{W}{S}$ is the wing loading in pounds per square foot; W is the weight of the airplane in pounds; and S is the effective wing area in square feet; a is the slope of the lift curve per radian.

On substituting (2) in (1), the relation

$$\Delta n = \frac{\frac{\rho_0}{2} ak}{\frac{W}{S}} \; VeU_e \qquad (3)$$

is obtained.

On inspection of this relation, it is to be noted that the increment of load factor produced by a given gust is not only a function of the design of the airplane, but is also to some extent under the control of the pilot. That is, the pilot may mitigate the effect of large gusts by reducing the airspeed, limited, of course, by controllability.

In order, to make the application of equation (3) to gust and fatigue data quantitative, some values for a hypothetical plane will be substituted in (3).

It will be assumed that:

1. The wing loading W/S is 28 pounds per square foot. (See reference 2, fig. 3.)

2. The K value corresponding to this (fig. 1, reference 1) is 1.11.

3. The slope of the lift curve is 4.7 (roughly an average value for airplanes of this size).

4. The cruising speed is 220 miles per hour or 323 feet per second (reference 2, fig. 1). If these values are used, (3) becomes

$$\Delta n = 0.0715 \quad U_e \tag{4}$$

The "load factor" for this hypothetical airplane at any given gust velocity is given by the relation

$$\begin{aligned} n &= 1 + \Delta n \\ &= 1 + 0.0715 \; U_e \end{aligned} \tag{5}$$

The limit load factor, as noted, is reached when U_e becomes 30 feet per second, or

$$n_L = 1 + 0.0715 \times 30 = 3.14$$

and the ultimate load factor (defined as 1.5 times the limit load factor) will be 4.71.

Thus, the gust velocity which will just develop the ultimate load factor will be:

$$U_e = \frac{n_u - 1}{0.0715} = \frac{4.71 - 1}{0.0715} = 51.8 \text{ feet per second}$$

and is considered to be applied at the center of gravity of the airplane.

It should be understood that the acceleration (and ther by the load factor) produced by a gust as computed above applies to the state of affairs at the center of gravity of the airplane. Individual parts of the airframe may have an acceleration different from that given by (3) for a given gust. Thus, in applying the analysis given in this report to detailed design, the designer should use the relation between gust velocity and acceleration pertaining to the part under consideration.

Relation between Load Factor and Stress

The next step in applying gust data to the fatigue problem is to develop a relation between load factor and stress.

In some cases, and particularly where redundant structures are involved, the stress at a given location in an airframe will not be directly proportional to the acceleration (or load factor) as computed; also, at different locations in the same airplane the relation between these two quantities may vary. Thus, for detailed design, the designer would need to know the exact relation between stress and acceleration for the part under consideration; however, for the purpose of illustration in this report it will be assumed that the equation relating stress and load factor is

$$\sigma = K_2 n \tag{6}$$

where K_2 is a constant and n is the load factor as given by (5).

For the purpose of this report the necessity for develop ing a method of evaluating K_2 can be avoided by the following expedient.

Let σ_{ult} be the ultimate strength of the part under consideration. This stress value will be reached when $n = n_{ult}$ and the percent of ultimate strength produced by any load factor is given by

$$P = \text{percent of ultimate strength} = \frac{\sigma}{\sigma_{ult}} \times 100$$

$$= \frac{K_2 n}{K_2 n_{ult}} \times 100 = \frac{n}{n_{ult}} \times 100 \tag{7}$$

By means of equations (3) and (7), and the design criterion (that limit load is produced by a 30-foot-per-second gust, and the ultimate load factor is 1.5 times the limit load factor) it is possible to compute the state of stress at any part in the wing structure in terms of the ultimate static strength of that part.

2. DISCUSSION OF GUST DATA

Rhode and Donely (reference 1) recently have published a compilation of flight data which they have used to develop some representative summation curves of the relative frequency of occurrence of atmospheric gusts. The information from reference 1 pertinent to this report is discussed below.

Summation Curves

Figure 1 (fig. 7 of reference 1) shows the summation curves developed by Rhode and Donely. The two curves A and B represent, respectively, the approximate upper and lower limits of the data available to them. The significance of points on these curves is given by the following illustration Point "a" on curve A indicates that out of 1,000,000 gusts there will be 3200 up gusts and 3200 down gusts having a velocity greater than 10 feet per second and 496,800 up gusts and 496,800 down gusts having a velocity less than 10 feet per second. It is to be noted that the data examined by Rhode and Donely indicate that there are an equal number of up and down gusts.

Note, also, that curve A stops at a gust velocity of ±40 feet per second. The significance of this is that gusts having a velocity greater than this value are so infrequent that the shape of the curve cannot be established on the bas of available data.

While summation curves such as those shown in figure 1 could be used directly, if fatigue information were complete enough, there are a number of practical reasons why it is more desirable to divide the summation curve into steps in which gusts within a given interval are lumped together; so the next step in relating gust and fatigue data is to chose a proper value for the gust class interval. The choice shoul satisfy the following requirements.

1. It should be large enough that the number of steps needed to approximate the summation curve can be reasonably reproduced in the laboratory.

2. It should be small enough that lifetimes predicted from its use are not too far different from those predicted by the summation curves themselves.

In analyzing data prior to the construction of summation curves, Rhode and Donely used a gust class interval of 4.5 feet per second. The use of this interval divides the range in gust velocity into 10 classes, which is a reasonable number as far as laboratory procedures are involved. As a first approximation, this interval was used in this report. A number of cases also were worked out for a gust class interval of 2 feet per second in order to find out whether a narrower class interval was necessary. It was found that the lifetimes predicted by the use of the 4.5-foot-per-second class interval differed from those predicted by the 2-foot-per-second class interval by less than 20 percent and in all cases were conservative - that is, the larger class interval predicted a shorter lifetime.

As will be shown later, the variation in lifetime produced by using the lower limit of Rhode and Donely's data (see fig. 1) instead of the upper limit is very much larger than 20 percent.

In view of this fact it does not seem unreasonable to use an approximation to the upper limit of Rhode and Donely's summation curves as a means of comparing the lifetimes of various structures.

The approximate gust frequency diagram which is used for this report is illustrated in figure 2. It is to be noted that the gust class interval is 4.5 feet per second, and that each class interval is characterized by the gust velocity, at the midpoint of that interval.

Distribution of Up and Down Gusts

The data examined by Rhode and Donely led them to the conclusion that there are about an equal number of up and down gusts; however, it is not yet possible to make a general statement as to the sequence of these gusts. That is, questions, such as

1. Is an up gust generally followed by a down gust?

2. Do large gusts generally occur together?

and so forth, cannot yet be answered with certainty.

It is not possible to develop a relation between the information on gusts and fatigue data without some knowledge as to the sequence of the gusts. Conversation with members

of the NACA and others who have examined a great many accele ometer records leads to the conclusion that it is more likel that an up gust is followed by a down gust than for two up c two down gusts to occur together. On this basis, it has bee assumed for the purpose of this report that up gusts are always followed by down gusts of equal magnitude. Figure 3 shows schematically two possible interpretations of gusts records. Figure 3b shows the type chosen for use in computation in this report. The type of gust sequence distribution chosen is equivalent to assuming that the increments in load factor are distributed around 1g loading as a mean value. In view of the fact that in some cases several up or down gusts may occur together, the assumption made as a basis for computation is a conservative one.

Minor Gusts

The gust data discussed so far are what Rhode and Donel term "major gusts." Superimposed on this major gust pattern is a pattern of minor gusts. There is not so much known about these superimposed gusts; however, there is enough known to allow them to be used in computations.

Rhode and Donely (reference 1, p. 19) state that there are about twice as many of these minor gusts as major ones. They also state that, while a few of these minor gusts were as large as 4.5 feet per second, the great majority were in the order of 0.3 feet per second.

For the purpose of this report the following assumption will be made regarding the minor gusts.

1. All minor gusts have a velocity of 2 feet per second. This assumption is conservative, since Rhode and Donely stat that the great majority have a velocity in the order of 0.3 feet per second and only a few are as large as 4.5 feet per second.

2. All minor gusts occur at the peaks of major gusts. This assumption obviously is conservative because, since peaks were counted, actually no minor gusts had peaks higher than the major gusts.

3. All the minor gusts are associated with the most damaging type of gust (that is, all minor gusts are associated with either up gusts or down gusts) and there are twice as many minor gusts as major gusts, or four times the number of pairs of major gusts.

This last assumption facilitates the use of available fatigue information. Figure 4 illustrates schematically the picture of minor gusts used as a basis for computation in this report.

The three foregoing assumptions for minor gusts obviously exaggerate their importance. This exaggeration is deliberate because, as will be shown later, even with this overemphasis on the severity of these gusts they contribute very little to shortening the lifetime of materials.

Number of Gusts per Mile of Operation

The preceding discussion gives the probable distribution in magnitude of gusts which might be encountered over a long period of time. In order to translate this information into service life of an airplane, it is necessary to know how often gusts are encountered. Rhode and Donely assumed that two cases should be considered - an airplane flying in turbulent air and one flying in still air. They define a term "path ratio" as the ratio of the length of path in turbulent air to the total length of path. Examination of data from widely separated sources indicated that this path ratio might vary from 0.005 to 0.24 with an average value of about 0.10.

The number of gusts encountered per mile of turbulent air depends on the size of the airplane. Rhode and Donely show that in turbulent air an airplane on the average encounters a gust every 11 chord lengths. For an airplane having a 10-foot mean chord this will amount to 48 gusts per mile. On the basis of the above, the total number of gusts per mile of operation (F) can be computed by the equation

$$F = \frac{480r}{\bar{c}} \tag{8}$$

when r is the path ratio as defined and $\bar{c}$ is the mean wing chord, in feet, for the airplane under consideration.

3. DISCUSSION OF DATA ON THE FATIGUE STRENGTH OF SOME AIRFRAME ELEMENTS

Conventional fatigue data are presented by means of what are called S - N curves. A point on such a curve represent

the number of cycles a part can endure of a stress cycle S.

There are many ways of designating this stress cycle. For example, S may represent the maximum stress in a cycle which extends from +S to -S, or it may represent a cycle having a maximum value S_1 and a minimum value S_2, or it may have other meanings. The curves also may have different meanings. That is, the points on a curve may represent a condition where the mean stress in the cycle is kept constant, or they may be drawn for the case where the ratio of minimum to maximum stress is kept constant, or other types of curves may be used by individual investigators. Thus, in using fatigue test data, it is necessary to know just what is meant by the curves.

In general, there is no hard and fast relation between the fatigue strength of a part and its static strength. In most cases, the static failure is accompanied by some ductility, while the fatigue failure is not. In a part such as a riveted joint, for example, the static failure may be shear failure in the rivets, while the fatigue failure may be by cracks in the sheet between rivets; so the type of static failure may have no apparent relation to the type of fatigue failure in the same part and may not be even in the same location. Nevertheless, for the purpose of this report it is convenient to express fatigue behavior in terms of static strength.

In many cases data are available which show that under a given static load an airframe part will fail by buckling, tearing, or some other form of catastrophic failure. The addition of fatigue data to the static data would provide information as to how many times the part under consideration could survive the repetition of a stress smaller than the one producing static failure without failing in fatigue. While it is always desirable to be able to express the load at failure in terms of the stress at the location of the failure it is not always practicable to do this, particularly with redundant structures. However, if the fatigue strength under a given loading cycle is expressed as a percentage of the load for ultimate static failure it is possible, by means of the scheme which will be outlined, to obtain some idea as to the lifetime of the structure under repeated loads without a detailed knowledge of the exact stress situation at every point.

Most of the laboratory fatigue information at present available, which is directly applicable to airframe structures, is in the form of so-called R curves (see reference 2, p.6). These curves constitute a family in which the maximum algebraic stress in a repeated stress cycle is plott against lifetime. Each curve of the family represents a different constant ratio of minimum to maximum stress. Figures 5 and 6 illustrate such families of curves on two widel different types of lap joint in aluminum sheet. In both of these the stress cycle applied was a direct stress; that is, no bending stresses were deliberately applied. These curves were plotted in terms of ultimate static strength as were suggested. In establishing curves of this type, it is general experience that a number of points are required, and there is invariably some scatter in results, so the curves really represent the center of scatter bands. Actual points are shown in figure 5 to illustrate the amount of scatter expected. In complex structures the scatter may be more thar indicated here. In view of the fact that obtaining data of this type is time consuming, most data available represent few R curves and in most cases the curves do not extend beyond 10,000,000 cycles.

In order to combine the gust and fatigue data, it is necessary to interpolate between R curves and also to extend data beyond 10,000,000 cycles. Based on experience with this type of data some rules for extrapolation and inte polation have been evolved which, it is believed, will produce results which are close to values that would be obtaine from actual measurements and which are "conservative." That is, the use of these rules should not lead to unsafe structures.

One of the considerations in formulating these rules wa provided by the convention discussed above, that up and down gust loadings are grouped around a mean load. The adoption of this convention leads to the conclusion that it would be desirable to have the fatigue data in terms of constant mean curves instead of the constant R type. Accordingly, the rules have been made convenient to obtain these constant mear curves.

The steps involved are:

1. Replot the data from constant R curves, such as that in figures 5 and 6, in terms of maximum versus mean load for constant lifetime. Figures 7, 8, 9, 10, 11, 12, and 13 illustrate curves of this type for different types of structures. For convenience in plotting these curves from the

R curve data, lines of constant R are plotted on the maximum load-mean load diagram. These lines are obtained from the equation

$$\frac{\text{mean load}}{\text{maximum load}} = \frac{R + 1}{2} \qquad (9)$$

On examining figures 7 to 13, it will be noted that the curves of constant lifetime are practically straight lines for ratios of from 0.25 to 0.75, and in figures 8 and 13, where data on low values of R were obtained, this linearity extends fairly well throughout the entire range in R. Furthermore, it will be noted from figures 8 and 13 that, if it is assumed that this relation is linear, stress values at low and negative values of R are conservative. On this basis, the method used to find fatigue strengths at R values, other than those for which there are actual data, is to draw straight lines through the points available and extend these to low values of R. The curves in figures 7 to 13 can be used to construct S - N curves for constant mean stress. Figure 14 shows a series of such curves plotted for a constant mean load of 21.2 percent of the ultimate strength. This value was chosen to fit with the illustrative example on gust loading given earlier in the report.

2. As was noted above, available fatigue data rarely extends to greater than 10,000,000 cycles. Some help in extending the constant mean curves to lifetimes longer than 10,000,000 cycles is obtained from figure 14. It will be noted that at 10^7 cycles the "constant mean" curves in figure 14 do not lie far above a stress value 21.2 percent of the ultimate strength. At 21.2 percent of the ultimate strength the lifetime should be infinite because this represents steady stress. From this fact, the slope of the extrapolated curve can be located within fairly close limits, furthermore, from data such as those of reference 3, which extend to over 100,000,000 cycles, it is seen that if the slope of the fatigue curve at 10^7 cycles is prolonged it will lie under the actual curve and will, therefore, be conservative. On these bases the method of extrapolating to long lifetimes used in this report is to extend the constant mean curve using roughly the slope at 10^7 cycles, making the curve intersect the point where the mean load equals the maximum load at 10^{12} cycles. By using this method, it is believed that the extrapolated curve will be close to, but somewhat under, the curve which would be obtained by actual measurement.

Fatigue Damage

Points on the fatigue curves just described were obtained by repeating a given stress cycle; however, in service, a part will be subjected to an irregular series of stress cycles. It is, therefore, important to know how much repeated loading at one stress cycle will affect the lifetime at another stress cycle, or in other words, how much damage is produced by a given stress cycle repeated "n" times.

There are not enough data available to allow this quantity to be handled precisely; however, there is enough known about damage in general to allow rules to be developed which will usually predict the effect of damage within the scatter band surrounding fatigue curves, and which in any case will lead to safe design.

The most careful work on fatigue damage has been done on steels; however, there has been some work on other metals. (See reference 4, p. 188-200.)

From this work the following general statements can be made regarding fatigue damage:

1. Repeated cycles of low stress usually have a strengthening effect. This is especially true with steels where the stress cycle is under the endurance limit; however, it is also true for nonferrous alloys up to a certain number of cycles.

2. While cycles of high stress are in general damaging, a certain number of these can be repeated without appreciably altering the number of cycles that can be endured at a lower stress level.

From the above it can be seen that repeated stresses can be both damaging and strengthening.

Recently, Miner (reference 5) has suggested a scheme whereby the effect of damage can be estimated quite closely at least for 24S-T Alclad.

His scheme is based on the assumption that every cycle at any stress produces some damage and that the damage produced by any stress cycle is proportional to the lifetime at that stress.

Thus, the life of a part under a stress spectrum can be computed from the equation

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \ldots = 1 \qquad (10)$$

where n_1 is the number of cycles at stress cycle S_1 having a potential life of N_1 cycles.

There are two unconservative aspects to this assumption.

1. It ignores the possibility that the damage may be greater for some stress cycles than would be predicted from direct proportionality.

2. Brueggeman, Mayer, and Smith (reference 6) have shown that the lifetime under a simple stress spectrum consisting of one series of high stresses and one series of low stresses depends on whether the high stress cycles or low stress cycles are applied first.

These unconservative aspects are, however, more than balanced by the following conservative factors.

1. The scheme attributes some damage to all stress cycles, whereas, the facts are that a certain number of cycles at any stress can be applied without producing appreciable damage.

2. Strengthening from under stressing is ignored. Since most of the stress cycles applied in service are at a low stress level, this factor is quite conservative.

3. While the findings of Brueggeman, Mayer, and Smith are correct when the high and low stress levels are sharply segregated, in service where high and low stresses are alternated the effect should be greatly minimized.

The usefulness of the scheme proposed by Miner has been checked experimentally both at the laboratories of the Douglas Aircraft Company, Inc. (reference 5) and at Battelle. At both places lifetimes predicted from equation (10) are within the scatter band for measured lifetimes for all cases tried so far.

4. THE COMBINATION OF GUST AND FATIGUE DATA

A number of cases have been worked out illustrating how gust and fatigue data can be combined. These examples have been based on the following factors:

1. In all cases examples have been worked out using the gust distribution curve shown in figure 2. In this figure the class interval is 4.5 feet per second. This distribution is based on the upper limit of Rhode and Donely's data.

2. Several cases are computed using a gust class interval of 2 feet per second to show that this interval predicts somewhat longer lifetimes and is, therefore, less conservative than the 4.5-foot-per-second interval.

3. A case has been worked out using the lower limit of Rhode and Donely's data and a 4.5-foot-per-second gust class interval. This case shows how much longer lifetimes are predicted from the use of their lower limit.

4. In all cases it is assumed that up and down increments in load factor are grouped around a g load as a mean value. The idealized shape of the major gust curve used is shown in figure 3b.

5. Several cases for widely different types of structural elements have been worked out showing the effect of minor gusts. The idealized shape of the minor gust pattern is shown in figure 4.

6. The airplane used for illustration is assumed to have the following characteristics:

(a) It is designed for limit load at a 30-foot-per-second gust.

(b) It has a cruising speed of 220 miles per hour.

(c) It has a limit load factor of 3.14 and an ultimate load factor of 4.71.

(d) At a load factor of $1g$ (zero gust velocity) the stress in a part under consideration is 21.2 percent of its ultimate strength (100/4.71).

7. In order to reduce the lifetime in gusts to miles or hours of operation it is assumed that the mean wing chord is 11 feet and the path ratio is 0.1.

8. The fatigue curves used for computations are shown in figure 14.

Tables 3, 4, 6, 7, 8, 9, 11, and 12 show the effect of major gusts computed in various ways. In these tables the various columns have the following significance:

Column 1 is the gust frequency distribution taken either from figure 2, which is based on a class interval of 4.5 feet per second or on a basis of 2 feet per second; the interval used is designated as the caption of the table. The numbers in this column are based on a total of 1,000,000 gusts.

Column 2 is the magnitude of the gust velocity at the midpoint of the interval.

Column 3 is the load factor in "g" units associated with the gust velocities in column 2 as computed by equation (5).

Column 4 is the maximum load in percent of ultimate strength associated with the load factors in column 3 as computed from equation (7).

Column 5 is the potential lifetime in cycles associated with the maximum loads in column 4 when the mean load is 21.2 percent of the ultimate strength. These values are obtained from the appropriate fatigue curve in figure 14.

Column 6 contains numbers which are the ratio of values in column 1 to those in column 5 expressed in percent. The figures in this column represent the amount of life exhausted by the number of gusts in a given class interval. The sum of all numbers in column 6 is the percentage of lifetime exhausted by 1,000,000 gusts having magnitude-frequency distribution shown in columns 1 and 2.

The life in miles associated with major gusts is computed from the equation

$$\text{Life in miles} = \frac{100}{\text{sum of col. 6}} \times \frac{1000000}{F} \qquad (11)$$

where F is computed by equation (8), using a path ratio of 0.1 and a mean chord of 11.0 feet, F is 4.37.

Tables 5 and 10 show the effect of minor gusts on two widely different types of lap joint.

In these tables the various columns have the following significance.

Column 1 is computed by multiplying the number of pairs of gusts in each class interval (fig. 2) by 4.

Column 2 is computed by adding 1 foot per second to the gust velocity representing each class interval. (See fig. 4.

Column 3 is computed from column 2 by means of equation (5).

Column 4 is the mean value for minor gusts and is the same as the maximum value for major gusts. (See col. 3 of tables 1, and etc.)

Column 5 is the lifetime associated with the maximum loads as given in column 3 and the mean loads as given in column 4. These lifetimes are read from curves constructed with the use of figures 7 and 13 and using the rules of extrapolation discussed above.

Column 6 contains values in column 1 divided by those in column 5 expressed as percent of total life.

The sum of values in column 6 is to be added to the similar value as obtained in tables 1, 3, 4, 6, 7, 8, 9, 11, and 12 to determine the lifetime exhausted by both major and minor gusts for 1,000,000 major gusts.

DISCUSSION OF RESULTS

In tables 1 to 12, lifetimes have been computed for a series of structural elements having widely different properties according to rules developed in this report.

These computations show both the limitations and the possibilities of the proposed scheme regarding the application of gust frequency data to fatigue information.

In order to utilize the fatigue data available it was necessary to deviate to some extent from recognized design practices. It is usual in design to compute skin stresses and then to make the joints strong enough to withstand these stresses whatever they may be. When this method is used, the joint may or may not be critical. The joints on which there were suitable data were not designed to develop maximum stresses in the sheet under the loading conditions used; therefore, all of the computations were made in terms of joint strength rather than sheet strength. By expressing all strengths in terms of percent of ultimate strength, however, the treatment has been made nonspecific as to just where failure must occur; therefore, the same principles used here could be made to apply to any design situation.

While the computations show that for various reasons, which will be listed below, it is not possible, at present, to predict unequivocally the life of a part in a given airplane, it is possible to obtain information about the relati lifetime of alternate designs, and there are certain other conclusions which appear to be reasonably secure regardless of future additions of information. Some conclusions based on the computations given in tables 1 to 12 are:

1. The major effect on lifetime in all lap joints is produced by gusts in the range from 4.5 to 9 feet per second; on sheet material the range is from 4.5 to 13.5 feet per second.

2. In all cases computed, gusts having a velocity greate than 26 feet per second have a negligible effect on lifetime barring, of course, gusts large enough to fail the structure statically.

3. Tables 5 and 10 show that for widely different types of lap joints minor gusts have very little effect on lifetime. This result is obtained in spite of the fact that the magnitude of minor gusts was exaggerated.

4. As was mentioned above, customary design procedure attempts to develop maximum allowable sheet stresses. For one row of rivets spaced 3/4 inch in 0.040 24S-T Alclad sheet, the static ultimate strength of the joint is reached when the stress in the sheet is only 23,100 psi. When this joint is operating at a load factor of 4.71 it will have a lifetime computed by the methods developed here of 19,300 hours. (See table 1.) If the number of rivets is doubled by inserting a second row, the stress in the sheet will be 48,200 psi when the joint is at its ultimate strength, a value more than double that obtained for a single row of rivets. However, if the joint containing two rows of rivets is subjected to the gust stress cycle at the same percentage of its ultimate strength its lifetime will be only 3240 hours. (See table 6.) Thus, while doubling the number of rivets will double the strength of the joint as judged by static tests, the stronger joint will not last so long when operated at the new strength level. Tables 7, 9, and 11 show that this same state of affairs applies to one and two rows of spot welds; however, the particular joint having three rows of spot welds investigated can operate at full strength and will have a life even longer than the single row joint operating at an equivalent strength level.

Many of the uncertainties in predicting the lifetime of airframe parts originate with the flight data. The most important sources of uncertaintity can be summarized as follows

1. The data examined by Rhode and Donely do not lead to a definite gust magnitude-frequency distribution. They, therefore, report two distribution curves representing the upper and lower limits of the data available to them. On comparing the data in table 1 (computed from curve A, fig. 1) with that in table 2 (computed from curve B, fig. 1) it is seen that the predicted life depends on whether the upper or the lower limit of Rhode and Donely data is used as a basis for computation. It is possible that as more data are accumulated this situation will be improved; however, it will probably never be possible to develop a universally applicabl distribution curve.

2. One of the most important gaps in present information is the lack of knowledge of the sequence of up and down gusts In this report it has been assumed that they are grouped in such a manner that the mean load factor can be considered to be 1g. This assumption is a conservative one and may be too conservative.

3. It has been assumed that the acceleration at the center of gravity of an airplane is directly proportional to the gust velocity (equation (1)); however acceleration at other locations may not be directly proportional, and the functiona relationship may be different in different airplanes. This same argument applies to the relation between acceleration and stress at any location in an airplane. In this report it has been assumed that both relations are linear; however, as more accurate information becomes available the methods developed in this report can be applied to any type of functiona relationship by merely substituting the true value of stress associated with each gust velocity instead of the valve predicted on the basis of direct proportionality.

CONCLUDING REMARKS

Since the examples in this report were confined to effec resulting from gust loading, they apply only to the wing struc ture of an airplane. Tail structures, landing gear, and so forth, are also subjected to repeated loads; however, these usually result from other sources than gusts. Nevertheless,

whenever the repeated load history of any part is known, it should be possible to apply the same method of analysis used here.

In providing the link between load history and fatigue data, the most important factor is the assumption used for estimating damage from repeated loads. The one used in this report was proposed by Miner. This assumption is open to criticism, and it is possible to demonstrate that, under certain specific loading cycles, it is not correct. (See reference 7.) The sequence of loading cycles, under which Miner's proposal does not hold for steels at least, is one in which all high loads are separated from all low loads. Since in service loading the loads are mixed, it seems possible that his proposal will hold much more closely for service loading than for idealized load sequences.

As noted in the report, Miner's proposal has already received some experimental verification for mixed loadings; however, in view of the importance of this assumption, it should receive further experimental study.

Battelle Memorial Institute,
Columbus, Ohio, May 15, 1945.

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TABLE 1

Life Data on Lap Joint Using One Row of AN426AD-5 Rivets in .040 - 24ST Alclad Sheet. Static Ultimate Strength as Measured = 693 Lbs./Rivet. See Figures 5, 7, and 14 for Data on Fatigue Strength. Computed For Gust Class Interval of 4.5 Ft./Sec.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load in % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	$> 10^8$	.435
54,000	6.75	1.484	31.5	2.0×10^6	2.70
5,000	11.25	1.805	38.4	3.0×10^5	1.67
500	15.75	2.125	45.2	1.0×10^5	.50
50	20.25	2.45	52.0	4.5×10^4	.111
5	24.75	2.77	58.8	2.0×10^4	.025
1	29.25	3.09	65.5	9.5×10^3	.0105
.3	33.75	3.41	72.4	4.2×10^3	.0071
.1	38.25	3.74	79.5	2.0×10^3	.0050
.03	42.75	4.06	86.2	8.5×10^2	.0035

Sum of Col. 6 = 5.467% life used in 10^6 gusts

Life = 18.3×10^6 gusts

= 4.25×10^6 miles (See equation 11)

= 19300 hours at 220 miles/hr.

TABLE 2

Life Data on Lap Joint Using One Row of AN426AD-5 Rivets in .040 24ST Alclad Sheet.
Computations Similar to Those in Table 1 Except That Lower Limit of Gust-Frequency Data (See Fig. 1) Has Been Used as a Basis For Computation
Gust Class Interval 4.5 Ft./Sec.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load In % of Ult.	5 N, Cycles	6 % of Life
488,000	2.25	1.161	24.6	10^8	.488
11,000	6.75	1.484	31.5	2.0×10^6	.550
850	11.25	1.805	38.4	3.0×10^5	.280
48	15.75	2.125	45.2	1.0×10^5	.048
6	20.25	2.45	52.0	4.5×10^4	.013
1	24.75	2.77	58.8	2.0×10^4	.005
.2	29.25	3.09	65.5	9.5×10^3	.002
.06	33.75	3.41	72.4	4.2×10^3	.0014
.02	38.25	3.74	79.5	2.0×10^3	.001
.01	42.75	4.06	86.2	8.5×10^2	.001

Sum of Col. 6 = 1.39% of life in 10^6 gusts

$$\text{Life} = \frac{100}{1.39} \times 10^6 = 72 \times 10^6 \text{ gusts}$$

$$= 16.5 \times 10^6 \text{ miles (See equation 11)}$$

$$= 75000 \text{ hours at 220 m.p.h.}$$

TABLE 3

Life Data on Lap Joint Using One Row of AN426AD-5 Rivets Spaced 3/4" In .040-24ST Alclad Sheet. Static Ultimate Strength as Measured = 693 Lbs. Rivet. See Figures 5, 7, and 14 For Fatigue Strength Data. Computation For Gust Class Interval of 2 Ft. Sec. See Table 1 for Computation on Gust Class Interval of 4.5 Ft./Sec.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load In % of Ult.	5 N Cycles	6 % of Life
295,000	1	1.071	22.8	10^9	.029
125,000	3	1.214	25.8	7×10^7	.178
50,000	5	1.358	28.8	6×10^6	.832
21,000	7	1.500	31.8	1.5×10^6	1.400
5,820	9	1.642	34.8	6×10^5	.970
2,100	11	1.785	37.8	3.4×10^5	.6188
690	13	1.930	40.9	2.0×10^5	.346
270	15	2.07	44.0	1.03×10^5	.262
88	17	2.21	46.8	9×10^4	.098
32	19	2.36	50.0	5.6×10^4	.057
11.7	21	2.50	53.0	3.8×10^4	.042
4.3	23	2.64	56.0	2.8×10^4	.0153
2.1	25	2.79	59.2	1.8×10^4	.0117
.9	27	2.93	62.2	1.03×10^4	.009
.38	29	3.07	65.0	1.0×10^4	.0038
.24	31	3.20	67.9	7.0×10^3	.0034
.17	33	3.36	71.2	5.0×10^3	.0034
.09	35	3.50	74.2	3.5×10^3	.0026
.05	37	3.64	77.2	2.5×10^3	.0020
.03	39	3.79	80.4	1.7×10^3	.0017
.01	41	3.93	83.4	1.03×10^3	.0009
.009	43	4.08	86.7	8×10^2	.0010
.003	45	4.22	89.5	6×10^2	.0005

Sum of Col. 6 = 4.88 % life used in 10^6 gusts

Life = 20.6×10^6 gusts

= 4.72×10^6 miles (See equation 11)

= 21400 hours at 220 m.p.h.

TABLE 4

Life Data on Lap Joint Using One Row of 5/8" - 17ST Hot Driven Rivets Spaced 1-7/8" in 1/4" - 17ST Sheet. See Figures 6, 8, and 14 for Data on Fatigue Strength. Computed for Gust Class Interval of 4.5 Ft./Sec.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load in % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	2×10^7	2.19
54,000	6.75	1.484	31.5	1×10^6	5.40
5,000	11.25	1.805	38.4	4×10^5	1.25
500	15.75	2.125	45.2	1.5×10^5	.332
50	20.25	2.45	52.0	6×10^4	.083
5	24.75	2.77	58.8	3×10^4	.016
1	29.25	3.09	65.5	1.5×10^3	.0066
.3	33.75	3.41	72.4	6×10^3	.0050
.1	38.25	3.74	79.5	3×10^3	.0033
.03	42.75	4.06	86.2	1.4×10^3	.0020

Sum of Col. 6 = 9.29% life used in 10^6 gusts

$$\text{Life} = \frac{100}{9.29} \times 10^6 = 10.8 \times 10^6 \text{ gusts}$$

$= 2.47 \times 10^6$ miles (See equation 11)

= 11250 hours at 220 m.p.h.

TABLE 5

The Effect of Minor Gusts on the Life of a Lap Joint Using One Row of AN426AD-5 Rivets in .040" - 24ST Alclad Sheet. See Table 1 For Computation on Major Gusts. See Text for Method of Computation.

1 Frequency of Minor Gusts In Each 1,000,000 Major Gust	2 U_e Sum of Major + Minor Gust	3 Load Factor, n	4 Max. Load % of Ult.	5 Mean of Minor Gusts in % of Ult.	6 N Cycles	7 % of Life
1,740,000	3.25	1.232	26.2	24.6	10^9	.174
216,000	7.75	1.555	33.0	31.5	10^9	.021
20,000	12.25	1.875	39.8	38.4	10^9	.002
2,000	16.75	2.200	46.7	45.2	10^9	.0002
200	21.25	2.520	53.5	52.0	10^9	negligible
20	25.75	2.830	60.0	58.8	10^9	"
4	30.25	3.16	67.0	65.5	10^9	"
1.2	34.75	3.48	73.8	72.4	10^9	"
.4	39.25	3.81	80.6	79.5	10^9	"
.12	43.75	4.13	87.2	86.2	10^9	"

Sum of Col. 7 = .198%

Contribution of minor gusts to lifetime using figure of 18.3 x 10^6 gusts as total lifetime (Table 2) contribution of minor gusts in 3.6% of total life.

TABLE 6

Life Data on Lap Joint Using Two Rows of AN426AD-5 Rivets in .040 - 24ST Alclad Sheet. Static Ultimate Strength as Measured = 725 Lbs./Rivet. See Figures 9 and 14 For Data on Faitgue Strength. Computed for Class Interval of 4.5 Ft./Sec. See Text for Method of Computation.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load, % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	10^8	.435
54,000	6.75	1.484	31.5	2.3×10^5	23.40
5,000	11.25	1.805	38.4	7.5×10^4	6.67
500	15.75	2.125	45.2	3.8×10^4	1.32
50	20.25	2.45	52.0	2.3×10^4	.22
5	24.75	2.77	58.8	1.3×10^4	.038
1	29.25	3.09	65.5	8×10^3	.0125
.3	33.75	3.41	72.4	4.8×10^3	.006
.1	38.25	3.74	79.5	2.9×10^3	.003
.03	42.75	4.06	86.2	1.7×10^3	.0017

Sum of Col. 6 = 32.1% life used in 10^6 gusts

$$\text{Life} = \frac{100}{32.1} \times 10^6 = 3.11 \times 10^6 \text{ gusts}$$

$$= .71 \times 10^6 \text{ miles (See equation 11)}$$

$$= 3240 \text{ hours at 220 m.p.h.}$$

TABLE 7

Life Data on Lap Joint Using One Row of Spot Welds Spaced 3/4" in .040-24ST Alclad Sheet. Static Ultimate Strength = 595 Lbs./Spot. See Figures 10 and 14 for Fatigue Strength. Computed for Gust Class Interval of 4.5 Ft./Sec. See Text for Method of Computation.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load, % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	10^8	.435
54,000	6.75	1.484	31.5	4.5×10^5	12.00
5,000	11.25	1.805	38.4	5×10^4	10.00
500	15.75	2.125	45.2	6×10^3	8.35
50	20.25	2.45	52.0	1×10^3	5.00
5	24.75	2.77	58.8	2.7×10^2	1.85
1	29.25	3.09	65.5	1.0×10^2	1.00
.3	33.75	3.41	72.4	5.8×10^1	.52
.1	38.25	3.74	79.5	2.1×10^1	.48
.03	42.75	4.06	86.2	6 • 0	.50

Sum of Col. 6 = 40.13% life used in 10^6 gusts

$$\text{Life} = \frac{100}{40.13} \times 10^6 = 2.49 \times 10^6 \text{ gusts}$$

$$= .57 \times 10^6 \text{ miles (See equation 11)}$$

$$= 2590 \text{ hours at 220 m.p.h.}$$

TABLE 8

Life Data on Lap Joint Using One Row of Spot Welds Spaced 3/4" in .040 - 24ST Alclad Sheet See Figures 10 and 14 for Fatigue Strength Data. Computed for Gust Class Interval of 2 Ft./Sec. See Table 7 for Computation on Basis of 4.5 Ft./Sec. See Text for Methods of Computation.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load in % of Ult.	5 N Cycles	6 % of Life
295,000	1	1.071	22.8	10^8	.295
125,000	3	1.214	25.8	1×10^7	1.25
50,000	5	1.358	28.8	1.5×10^6	3.34
21,000	7	1.500	31.8	4×10^5	5.25
5,820	9	1.642	34.8	1.5×10^5	3.88
2,100	11	1.785	37.8	6×10^4	3.50
690	13	1.930	40.9	2.5×10^4	2.76
270	15	2.07	44.0	1.0×10^4	2.70
88	17	2.21	46.8	4.5×10^3	1.95
32	19	2.36	50.0	1.7×10^3	1.89
11.7	21	2.50	53.0	8×10^2	1.46
4.3	23	2.64	56.0	4.5×10^2	.95
2.1	25	2.79	59.2	2.5×10^2	.84
.9	27	2.93	62.2	1.03×10^2	.87
.38	29	3.07	65.0	1.0×10^2	.38
.24	31	3.20	67.9	5×10^1	.48
.17	33	3.36	71.2	2.5×10^1	.68
.09	35	3.50	74.2	1.05×10^1	.90
.05	37	3.64	77.2	9	.55
.03	39	3.79	80.4	6	.50
.01	41	3.93	83.4	4	.25
.009	43	4.08	86.7	2.5	.36
.003	45	4.22	89.5	2.0	.15

Sum of Col. 6 = 35.09% life used in 10^6 gusts

$$\text{Life} = \frac{100}{35.09} \times 10^6 = 2.85 \times 10^6 \text{ gusts}$$

$$= .65 \times 10^6 \text{ miles (See equation 11)}$$

$$= 2960 \text{ hours at } 220 \text{ m.p.h.}$$

TABLE 9

Life Data on Lap Joint Using Two Rows of Spot Welds in .040 - 24ST Alclad Sheet. Spots Spaced 3/4" in Rows, Rows Spaced 1/2", Spots Staggered Static Ultimate Strength = 550 Lbs./Spot. See Figures 11 and 14 for Fatigue Data. Computation for Gust Class Interval of 4.5 Ft./Sec. See Text for Method of Computation.

1 Frequency of Occurrence In 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load, % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	10^8	.435
54,000	6.75	1.484	31.5	2.5×10^5	21.60
5,000	11.25	1.805	38.4	2.7×10^4	18.50
500	15.75	2.125	45.2	6.5×10^3	7.70
50	20.25	2.45	52.0	1.7 xx10^3	2.92
5	24.75	2.77	58.8	5.2×10^3	.96
1	29.25	3.09	65.5	1.7×10^2	.59
.3	33.75	3.41	72.4	6×10^1	.50
.1	38.25	3.74	79.5	2×10^1	.50
.03	42.75	4.06	86.2	6.5	.46

Sum of Col. 6 = 53.98% of life in 10^6 gusts

$$\text{Life} = \frac{100}{53.98} \times 10^6 = 1.85 \times 10^6 \text{ gusts}$$

$$= .423 \times 10^6 \text{ miles (See equation 11)}$$

$$= 1920 \text{ hours at 220 m.p.h.}$$

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TABLE 10

The Effect of Minor Gusts on the Life of a Lap Joint Using Two Rows of Spot Welds in .040 - 24ST Alclad Sheet. See Table 9 for Computation on Major Gusts. See Text for Method of Computation.

1 Frequency of Minor Gusts in Each 1,000,000 Major Gust	2 Ue, Sum of Major and Minor Gusts, Ft./Sec.	3 Load Factor, n	4 Max. Load, % of Ult.	5 Mean of Minor Gusts in % of Ult.	6 N, Cycles	7 % of Life
1,740,000	3.25	1.232	26.2	24.6	3×10^5	.58
216,000	7.75	1.555	33.0	31.5	8×10^8	.028
20,000	12.25	1.875	39.8	38.4	9×10^8	.0022
2,000	16.75	2.20	46.7	45.2	10^8	.0020
200	21.25	2.52	53.5	52.0	10^8	negligible
20	25.75	2.83	60.0	58.8	10^8	"
4	30.25	3.16	67.0	65.5	10^8	"
1.2	34.75	3.48	73.8	72.4	10^8	"
.4	39.25	3.81	80.6	79.5	10^8	"
.12	43.75	4.13	87.2	86.2	10^8	"

Sum of Col. 7 = .61%

Contribution of minor gusts to lifetime using 1.85×10^6 gusts as total lifetime (See Table 9) contribution of minor gusts is 1.13% of total life.

TABLE 11

Life Data on Lap Joint Using Three Rows of Spot Welds in .040 - 24ST Alclad Sheet. Spots Spaced 3/4" in Rows, Rows Spaced 1/2", Spots Staggered in Adjacent Rows. Static Ultimate Strength = 493 Lbs./Spot. See Figures 12 and 14 for Fatigue Strength Data. See Text for Method of Computation.

1 Frequency of Occurrence in 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load, % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	9×10^6	4.82
54,000	6.75	1.484	31.5	3.5×10^5	15.40
5,000	11.25	1.805	38.4	5.2×10^4	9.60
500	15.75	2.125	45.2	1.4×10^4	3.58
50	20.25	2.45	52.0	4.5×10^3	1.11
5	24.75	2.77	58.8	1.6×10^3	.31
1	29.25	3.09	65.5	5.0×10^2	.20
.3	33.75	3.41	72.4	1.5×10^2	.20
.1	38.25	3.74	79.5	5.2×10^1	.19
.03	42.75	4.06	86.2	1.5×10^1	.20

Sum of Col. 6 = 35.61% of life in 10^6 gusts

$$\text{Life} = \frac{100}{35.61} \times 10^6 = 2.8 \times 10^6 \text{ gusts}$$

$$= .64 \times 10^6 \text{ miles (See equation 11)}$$

$$= 2920 \text{ hours at 220 m.p.h.}$$

TABLE 12

Life Data on .040" - 24ST Alclad Sheet. Static Ultimate Strength = 67,000 p.s.i. See Figures 13 and 14 for Data on Fatigue Strength Computation for Gust Class Interval of 4.5 Ft./Sec. See Text for Methods of Computation.

1 Frequency of Occurrence in 1,000,000 Gusts	2 Mean U_e, Ft./Sec.	3 Load Factor, n	4 Max. Load, % of Ult.	5 N, Cycles	6 % of Life
435,000	2.25	1.161	24.6	7×10^{10}	.0043
54,000	6.75	1.484	31.5	3×10^{8}	.018
5,000	11.25	1.805	38.4	1.5×10^{6}	.332
500	15.75	2.125	45.2	2.8×10^{5}	.178
50	20.25	2.45	52.0	1.1×10^{5}	.045
5	24.75	2.77	58.8	6.2×10^{4}	.008
1	29.25	3.09	65.5	4.0×10^{4}	.0025
.3	33.75	3.41	72.4	2.5×10^{4}	.0012
.1	38.25	3.74	79.5	1.6×10^{4}	.0006
.03	42.75	4.06	86.2	1.05×10^{4}	.00028

Sum of Col. 6 = .59% of life in 10^6 gusts

$$\text{Life} = \frac{100}{.59} \times 10^6 \text{ miles} = 170 \times 10^6 \text{ gusts}$$

$$= 38.9 \times 10^6 \text{ miles (See equation 11)}$$

$$= 177{,}000 \text{ hours at 220 m.p.h.}$$

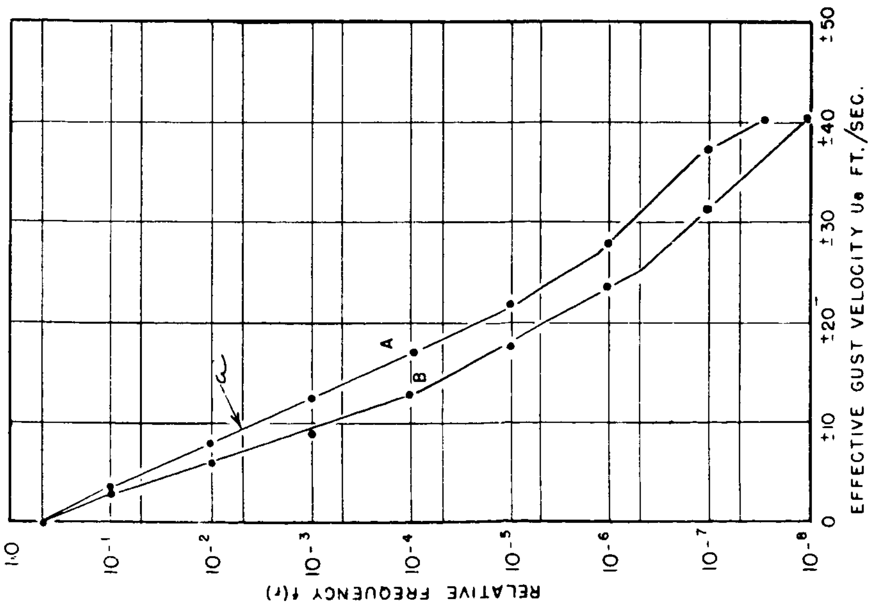

FIGURE 1.- UNIT SUMMATION CURVES DEFINING APPROXIMATE LIMITS OF GUST MAGNITUDE FREQUENCY DATA FROM NACA ARR L 4I21

$f(r) = \frac{\text{NO. OF GUSTS GREATER THAN } U_e}{\text{TOTAL NO. OF GUSTS}}$

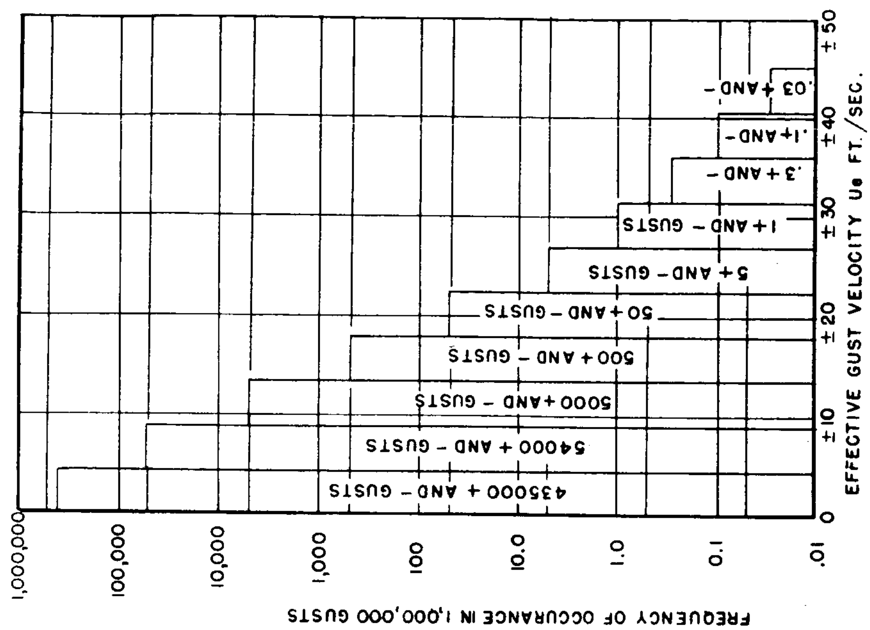

FIGURE 2.- APPROXIMATE GUST MAGNITUDE DISTRIBUTION IN 1,000,000 GUSTS USING CLASS INTERVAL OF 4.5 FT. SEC. BASED ON UPPER LIMIT OF SUMMATION CURVES (FIG. 1)

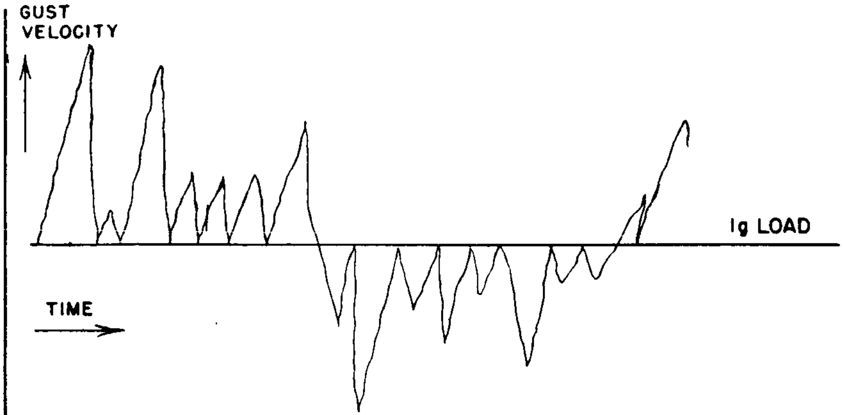

FIGURE 3a.- SCHEMATIC TYPE OF GUST VELOCITY - TIME RECORD WHERE "UP" GUSTS AND "DOWN" GUSTS ARE SEGGREGATED.

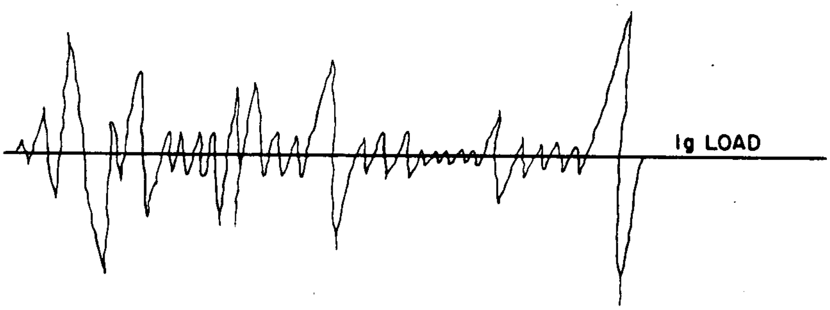

FIGURE 3b - SCHEMATIC TYPE OF GUST VELOCITY - TIME RECORD WHERE "UP" AND "DOWN" GUSTS ARE GROUPED AROUND A MEAN LOAD OF Ig THIS TYPE OF RECORD IS USED FOR ILLUSTRATION IN THIS REPORT

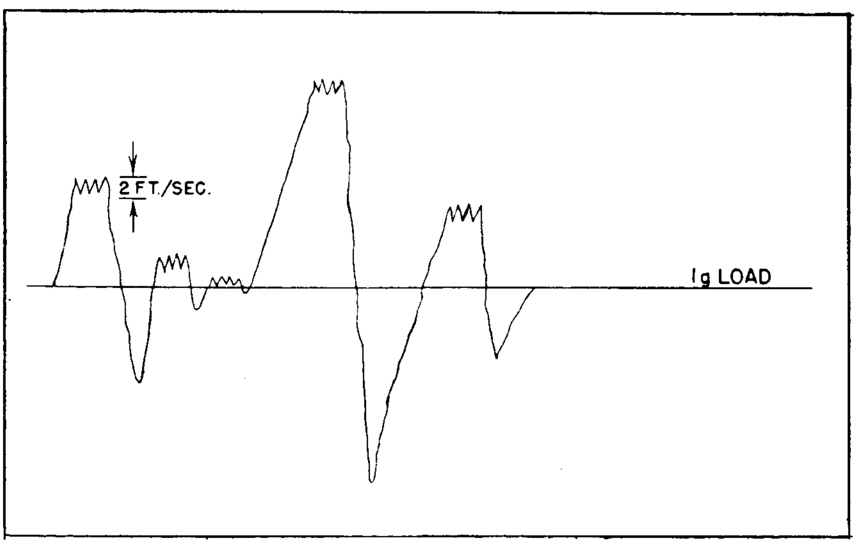

FIGURE 4.- SCHEMATIC ILLUSTRATION OF CASE WHERE MINOR GUSTS ALL OCCUR AT MAXIMUM OF MAJOR GUSTS THIS TYPE OF RECORD IS USED FOR DISCUSSION OF THE EFFECT OF MINOR GUSTS

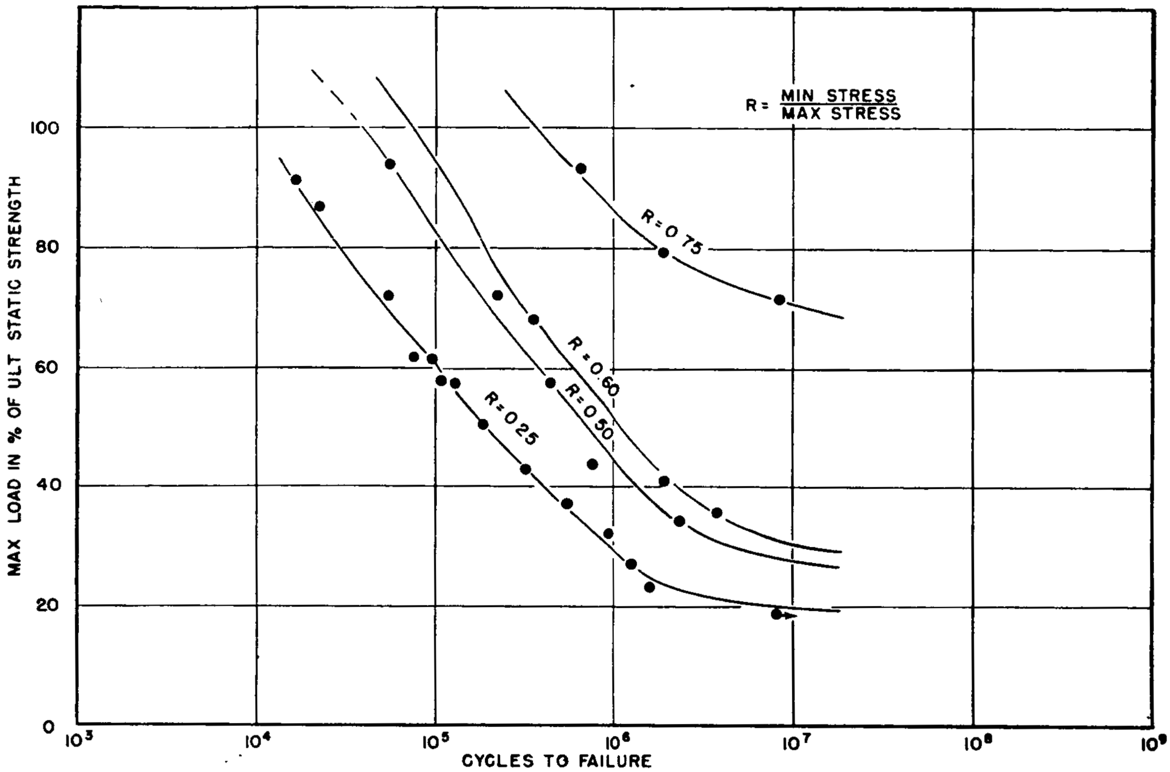

FIGURE 5.- S-N CURVES AT CONSTANT STRESS RATIO FOR RIVETED JOINTS IN 0.040 INCH 24S-T SHEET. ONE ROW OF AN426 AD-5, 100° COUNTERSUNK $\frac{5}{32}$" DIAM. RIVETS SPACED $\frac{3}{4}$" APART. DATA FROM NACA ARR NO 4F01, p.38. ULT. STATIC STRENGTH = 693 LBS/RIVET (6 RIVETS IN $4\frac{1}{2}$" WIDTH)

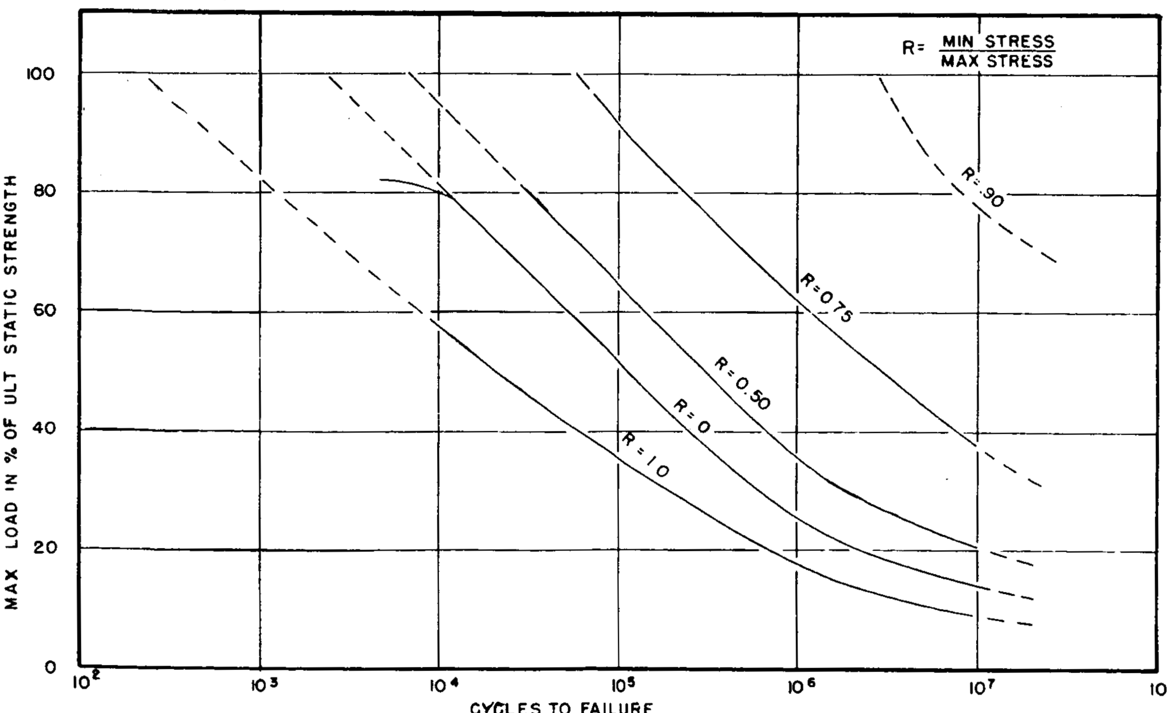

FIGURE 6.- S-N CURVES AT CONSTANT STRESS RATIO FOR RIVETED JOINT IN $\frac{1}{4}$" 17S-T PLATE ONE ROW (4 RIVETS) OF $\frac{5}{8}$" HOT DRIVEN 17S-T RIVETS. SPACED $1\frac{7}{8}$". DATA FROM UN-PUBLISHED REPORT FROM LABORATORIES OF ALUMINUM CO OF AMERICA

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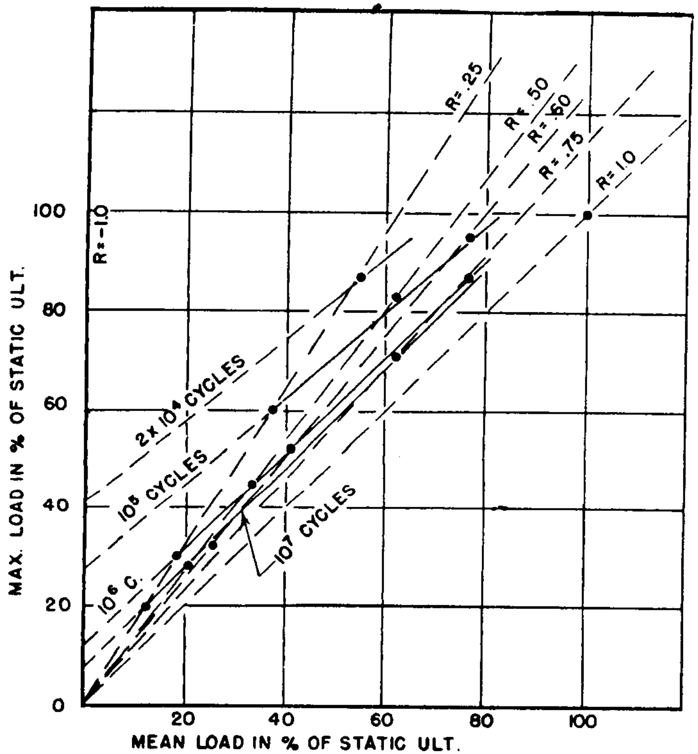

FIGURE 7.- CONSTANT LIFE CURVES. 1 ROW AN 426 AD-5 RIVETS SPACED $\frac{3}{4}$" IN .040" 24S-T ALCLAD (SEE FIG. 5) DATA FROM NACA REPORT ARR 4F01 p.38 ULT. STATIC STRENGTH = 693 LBS./RIVET

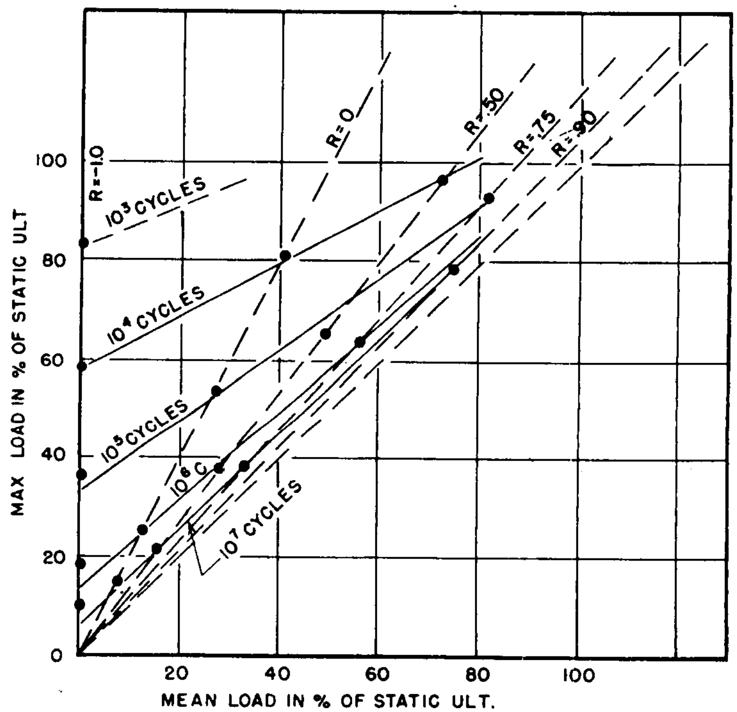

FIGURE 8.- CONSTANT LIFE CURVES. 1 ROW OF $\frac{5}{8}$" HOT DRIVEN 17S-T RIVETS IN $\frac{1}{4}$" 17S-T PLATE. DATA FROM UNPUBLISHED REPORT FROM ALUMINUM CO. OF AMERICA LABORATORIES.

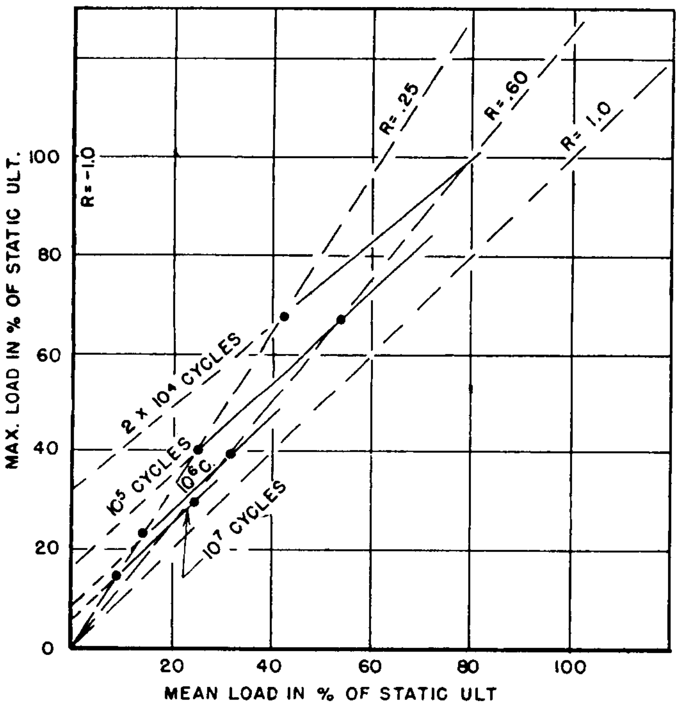

FIGURE 9.- CONSTANT LIFE CURVES. 2 ROWS OF AN 426 AD-5 $\frac{5}{32}$" RIVETS SPACED $\frac{3}{4}$" IN ROWS, ROWS $\frac{3}{4}$" IN 0.040" 24S-T ALCLAD SHEET. DATA FROM NACA REPORT ARR 4F01 p.39
ULT. STATIC STRENGTH = 725 LBS./RIVET

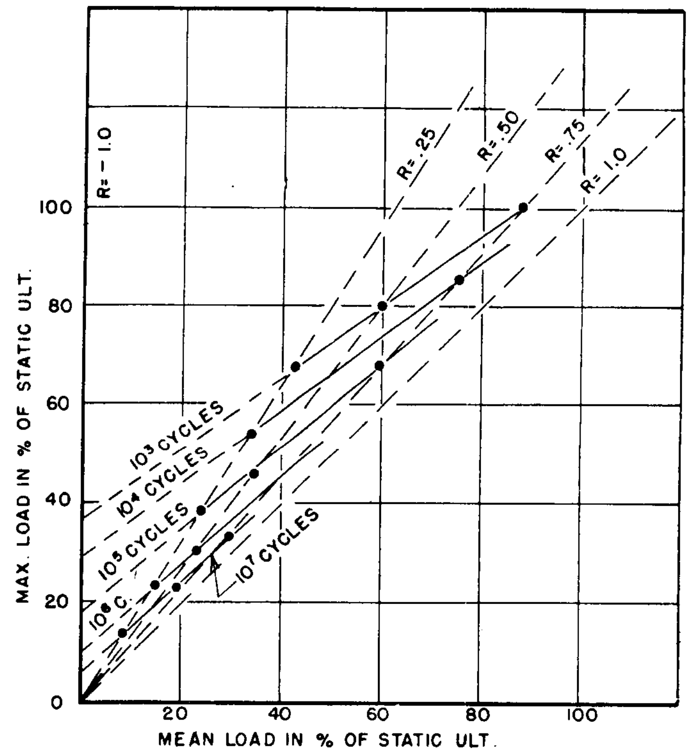

FIGURE 10.- CONSTANT LIFE CURVES. 1 ROW SPOT WELDS SPACED $\frac{3}{4}$" IN 0.040" 24S-T ALCLAD SHEET
DATA FROM NACA ARR 3F16 p 45 ULT. STATIC STRENGTH = 595 LBS./SPOT

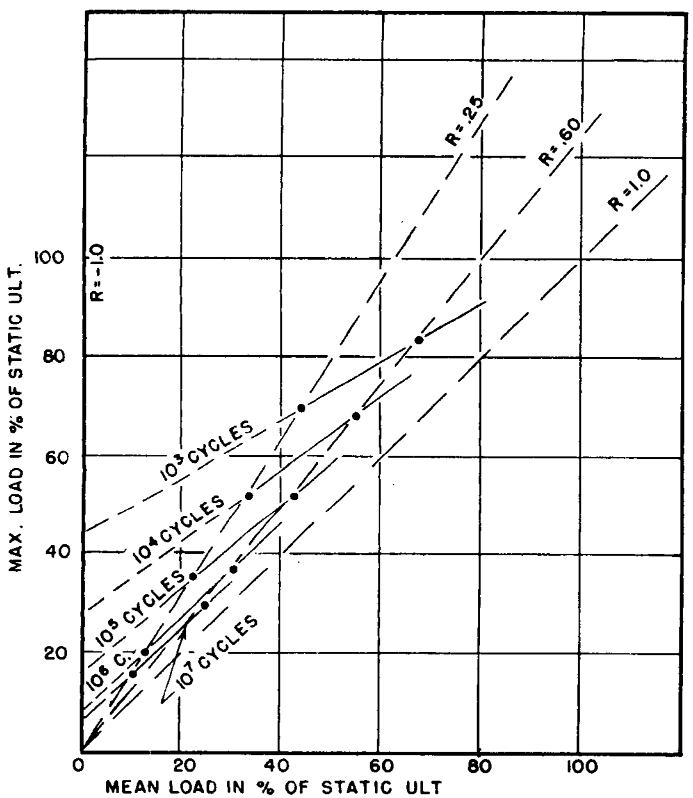

FIGURE 11.- CONSTANT LIFE CURVES. 2 ROWS SPOT WELDS SPACED $\frac{3}{4}$" IN ROWS ROWS $\frac{1}{2}$" APART SPOTS STAGGERED LAP JOINT IN .040" 24 S-T ALCLAD SHEET DATA FROM NACA ARR 4 FOI p 32 ULT. STATIC STRENGTH = 550 LBS./SPOT

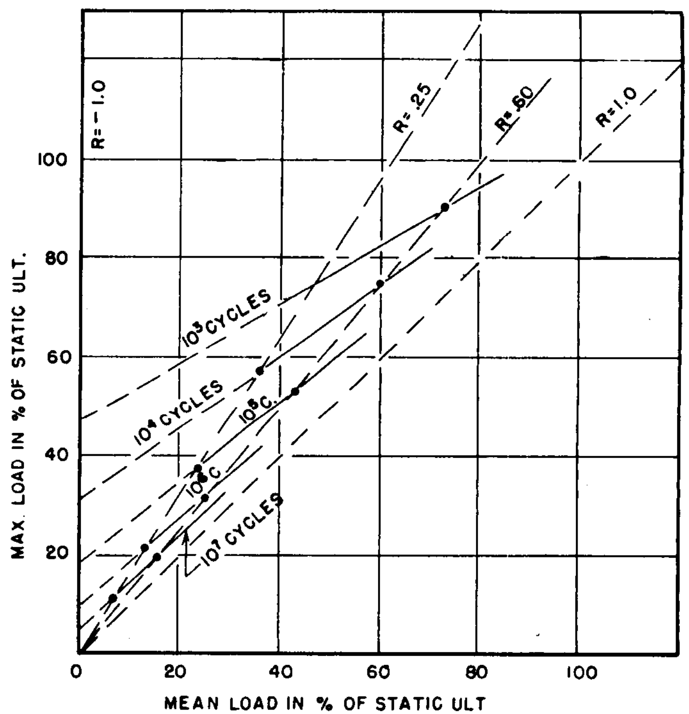

FIGURE 12.- CONSTANT LIFE CURVES 3 ROWS SPOTS SPACED $\frac{3}{4}$" IN ROWS, ROWS $\frac{1}{2}$" APART, SPOTS IN ADJACENT ROWS STAGGERED IN 0.040" 24S-T ALCLAD SHEET DATA FROM NACA ARR 4 FOI p.33 ULT STATIC STRENGTH = 493 LBS./SPOT

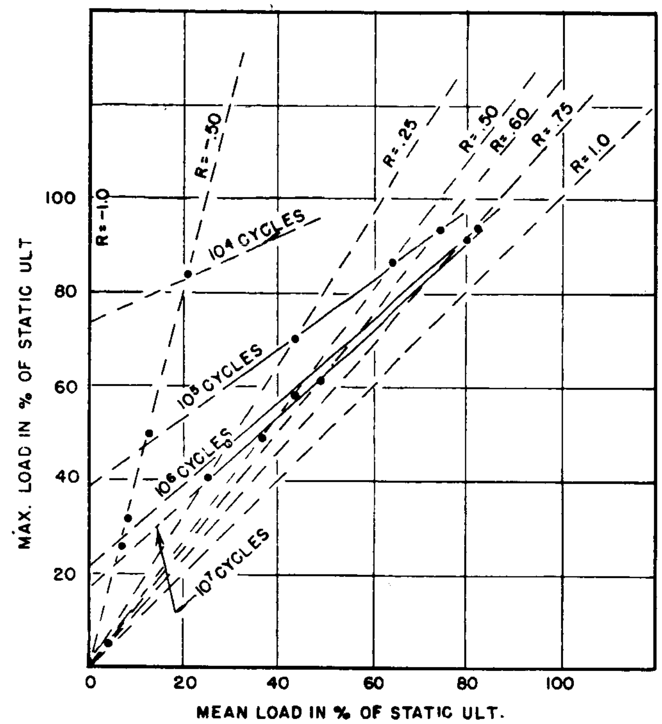

FIGURE 13.- CONSTANT LIFE CURVES FOR 24S-T ALCLAD SHEET 0.040" THICK. DATA FROM NACA ARR 4E30 p. 12 (DATA ON R=-.50 NOT PREVIOUSLY PUBLISHED) ULT STATIC STRENGTH = 67,000 psi

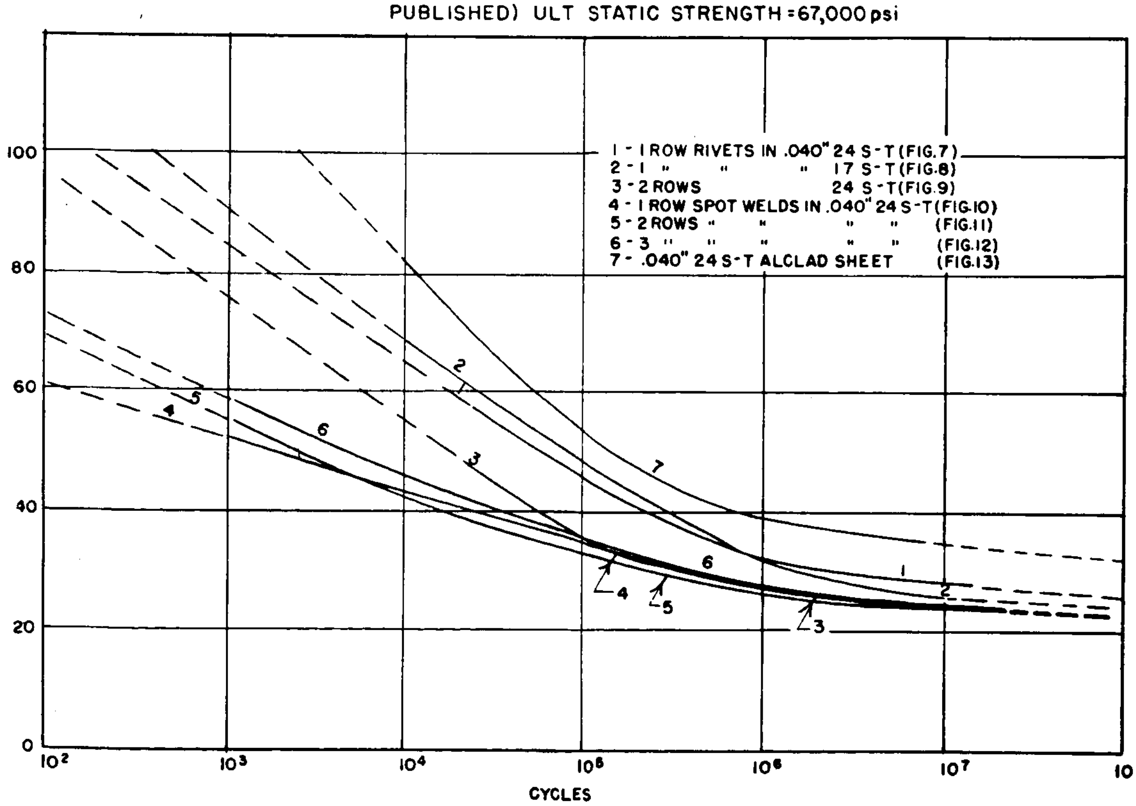

FIGURE 14.- S-N CURVES AT A CONSTANT MEAN LOAD OF 21.2 % OF THE ULTIMATE STATIC STRENGTH OF VARIOUS LAP JOINTS.